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TRANSIENT MODELLING OF MULTI-PASS SOLAR THERMAL COLLECTOR WITH SENSIBLE ENERGY STORING MATRIX

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ABSTRACT

Transient modelling of multi-pass solar hot air dryer as a physical system is presented in this present work. SIMSCAPE/SIMULINK tool was utilized for the theoretical study of hot air passing through transparent flat plates and anodized aluminium as solar thermal collector. Pebble bed made of granite was obtained locally to sever as the sensible heat reservoir. The thermal energy balance was resolved using lumped component technique. The parameters, variables and operating conditions of materials that constitute the thermal system forms the modelling input with available weather data collected in the Solar Research Site, Universiti Teknologi PETRONAS (4.385693^o N and 100.979203^o E). The model revealed improved on the multi-pass system performance efficiency by 12.4% and 10.1% when compared to the reported single pass and double pass solar air heaters. Closed loop control mechanism was imposed to achieve a steady heat flow 471.2 Js^{-1} to the drying compartment. A temperature gradient of 31.21 K was predicted which is suitable for the drying operation of many agricultural products. The theoretical result was in agreement with output obtained from the humidity controlled drying test system in the Solar Energy Laboratory, Universiti Kebangsaan Malaysia. However, there was need to improve the boundary condition accuracy and flexibility to accept various materials for system boundary.

Keywords: solar thermal collector, storing matrix, lumped component technique.

INTRODUCTION

The determination to achieve the United Nations target of green energy for all by 2050 is gaining momentum by contribution of researchers and other stakeholders in renewable energy sector. Every human being is becoming interested in energy that is economical and devoid of environmental pollution. Therefore, the green energy sector is now enjoying agencies and government supports on its research and development. A lot of approaches have been used in the past to dry farm products which are not eco-friendly such as burning of fossil fuel. A green active solar dryer was modelled as an alternative to unfriendly means of drying in our environment.

Numerical method has significant value in solving practical engineering challenges that other approach may be difficult to handle based on its iterative approach[1]. Numerical tool was used to investigate the effect of various sizes and operating variables on both flat and corrugated solar collector [2]. Flat absorber is the simplest, economical and the best thermal energy collector type for air heating applications [3]. The transient state in thermal conduction in solid material is usually aided by heat transfer by convection to or from liquid that form the solid material boundary [4], whereas Osório and Carvalho [5] affirmed that transient testing approach of solar absorber required less testing time when compared with other available solar collector testing techniques. Kong *et al.*[6] developed a transient method of solar collector testing by solving energy balance equations using Laplace transform technique.

Simulation of renewable energy system started in the second half of the twentieth century and hundreds of modelling software was used in the last two decades to solve solar energy related problems. However, each software is transient and has its peculiar vantage and limitation [3]. A heuristic solar collector model based on numerical approach was used to determine the absorber performance through variation in temperature [7].SIMSCAPE™ is a MATLAB oriented lumped object modelling tool and it is compliant with SIMULINK® environment [8].

Drying is the combination of thermal transfer from a solar collector or any other heat source to the crop to be dried and the mass transfer of water content of the crop from within to the atmosphere [9]. Solar drying is an economical means of preserving agricultural products with ease in transportation [10].

Many solar air heaters have been proposed and constructed. However, the statistic still revealed that many farmers are still using open drying mode of crop preservation[11]. This work is to achieve a theoretical investigation of crop dryer using robust SIMSCAPE modeling tool. A product that would be affordable to small and medium scale farmers with low system maintenance cost is predicted. Hence, a multi-pass collector that can generate hot air at a suitable temperature range[10, 12] for drying of crops and medicinal herbs under dynamic mode is the critical thrust of this work.

Fundamental principles

The conservation law forms the basis of more complex mathematical or engineering models including thermal and mass transfer systems which are the focus of this work [1]. The thermal energy equation for a dynamic condition is shown in Equation. (1).

$$\lambda^{-1}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{Q}}{k} \tag{1}$$

k is the material thermal conductivity, $\dot{Q}$ is the rate of heat transfer from the system source where λ can be evaluated by using Equation. (2).

$$\lambda = \frac{k}{C_p \rho} \tag{2}$$

Equation (3) is a first order, nonlinear ordinary differential equation with assumption that the heat source is not significant or absent.

$$V\rho \frac{dT}{dt} = -\left[A\rho\varepsilon\left(T^4 - T_1^4\right) + Ah\left(T - T_{amb}\right)\right] \tag{3}$$

The typical solar absorber thermal energy balance is expressed in Equation. (4)

$$\frac{\partial^2 T}{\partial z^2} Q_T = \alpha\tau I_s A_p \tag{4}$$

Equation (5) depicts the thermal balance between the transparent outer cover and the ambient while the boundaries are changed to get the Equation for the inner glass cover.

$$h_r\left(T_p - T_{g1}\right) = h_g\left(T_g - T_{amb}\right) - h_{g-f}\left(T_g - T_f\right) \tag{5}$$

Equation (6) shows the thermal transfer around the absorber that harvests the solar energy.

$$I_t = \Phi\left(T_p - T_{ch}\right) + h_r\left(T_p - T_g\right) + h_{p-f}\left(T_p - T_f\right) \tag{6}$$

The radiative heat transfer coefficient is obtained by substituting Equation. (8) into Equation. (7).

$$h_r = \frac{\left(T_p^4 - T_{g2}^4\right)}{\sum \varepsilon\left(T_p - T_{g2}\right)} \tag{7}$$

$$\sum \varepsilon = \varepsilon_{g2}^{-1} + \varepsilon_p^{-1} - 1 \tag{8}$$

The hot air stream temperature is valued by Equation. (9).

$$\phi \frac{dT}{dx} = A_p\left[h_{g1-f}\left(T_{g1} - T_f\right) + h_{g2-f}\left(T_{g2} - T_f\right)\right] \tag{9}$$

The thermal and mass transfer in the drying material is modelled based on an expression which defined the temperature and moisture gradient that determine the flow direction of moisture content of any material to be dried. The pressure component of Equation. (10) and Equation. (11) that are credited to Luikov has no significant impact on moisture movement [13].

$$\frac{\partial M}{\partial t} = \nabla^2 C_{1,1} M + \nabla^2 C_{1,2} T \tag{10}$$

$$\frac{\partial T}{\partial t} = \nabla^2 C_{2,1} M + \nabla^2 C_{2,2} T \tag{11}$$

A means of evaluating the significance in material temperature variation was done in this study by using the expression in Equation. (12) as ratio of convection resistance at the surface of the body to the conduction resistance within the material. However, if $B_i < 0.1$ the material is lumped element [14].

$$B_i = \frac{lh}{k} \tag{12}$$

Assumptions and approximation

The following assumptions were made to simplify some situations that would have been complex procedures and simplification of some equations required to model the drying system. However, careful consideration was taken to weigh the impact of the assumptions on the outcome of the system model and its operation.

- Air temperature varies in the direction of flow.
- Temperature gradient between the crop and its container in the drying chamber was not significant.
- The system mean air mass flow rate was considered.
- Isotropic materials are proposed to from the system composition.
- The absorber plate considered is thin and its conduction thermal transfer was neglected.

System modelling topology

The multi-pass model window is as shown in Figure. 1. The SIMULINK® / SIMSCAPE™ environment of MATLAB version 8.5.0.197613 (R2015a) was utilized to study the system using a dynamic mode approach. This

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model is classified into five sub-units videlicet: (a) Thermal source, (b) Glazing-1, (c) Glazing-2, (d) Collector, (e) Porous matrix, and (f) Closed loop. The air heater was simulated for 36000 s. A constant air flow rate of 0.05 kgs^{-1}[15] was used and daily relative humidity range of 55-100% was considered. The environmental temperature of 304 K was employed in this model and other thermal transfer constants and parameters were taken from reported studies. Table-1 shows some of the constants, air heater design and operating parameters.

The numerical equations were generated based on the various thermal components that constitute the solar drying system. The equations were solved numerically during the simulation to achieve the desired drying system model.

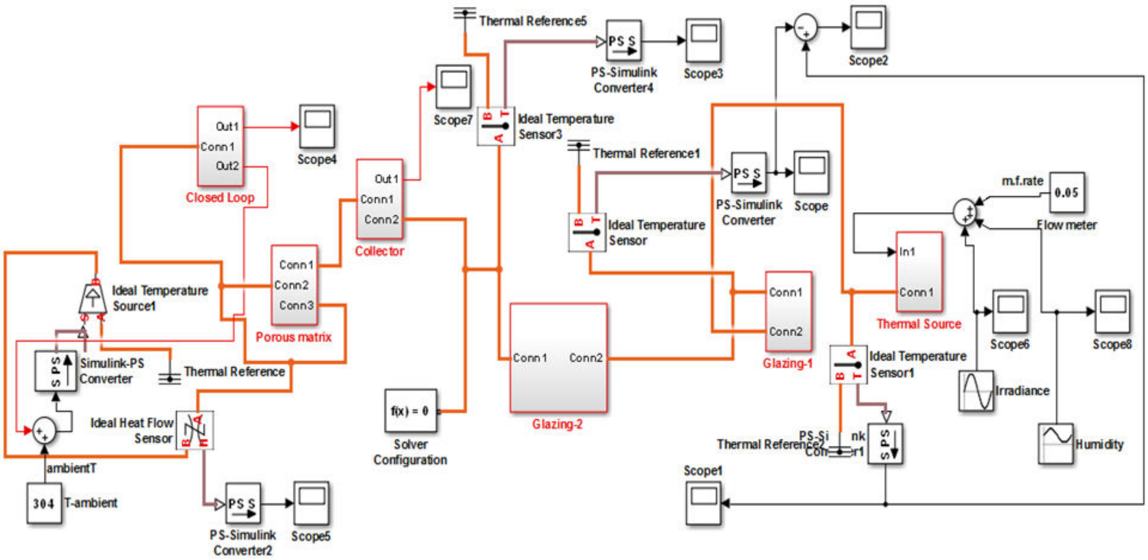

Figure-1. SIMULINK/SIMSCAPE modelling topology.

Table-1. Constants and parameters used for simulation.

Description	Symbol	Magnitude
Ambient Temperature	T_{amb}	304 K
Air mass flow rate	$\dot{m}$	0.05 kgs^{-1}
Humidity range	h	55-100%
Wind velocity	V_w	5 ms^{-1}
Collector plate area	A_p	1.56 m^2
Porous matrix surface area	A_{matrix}	2.5 m^2

RESULTS AND DISCUSSIONS

The solar irradiance pattern used during simulation of the solar air heater is shown in Figure-2. The daily peak solar energy flux was 854.8 Wm^{-2} while the early and late parts of the day were lower values. The environmental humidity was considered in this modelling. The midday relative humidity ratio was assumed to be 0.58.

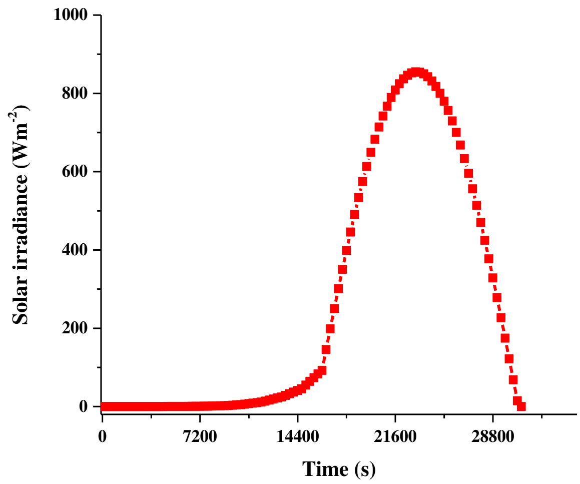

Figure-2. Solar irrandiance profile.

The temperature gradient obtainable in various systems is displayed in Figure-3 and the multi-pass approach was best in performance as the temperature gradient is an important function of drying system performance. However, the gradient reported could be improved for all systems based on the available solar irradiance.

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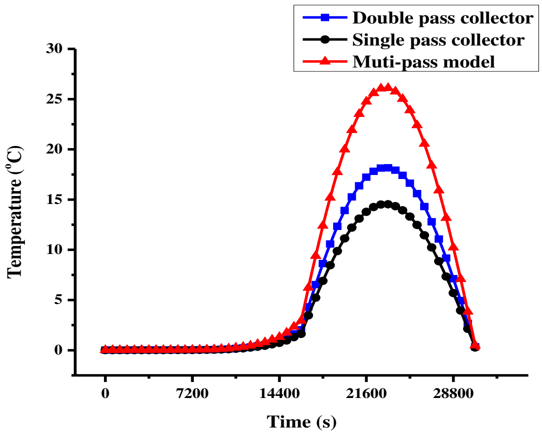

Figure-3. Temperature gradient of air heaters.

The air heater efficiency was enhanced by using second cover to reduce the thermal energy loss from system to the surrounding. Figure 4 shows the temperature profiles of the three modes considered in this study. Initially there was no difference in temperature until when the system temperature was elevated to about 13 K above the ambient. The difference was well shown around the midday which is depicted on the profile as 326.2 K, 319.8 K and 307.0 K for multi-pass, double pass and single pass collectors respectively.

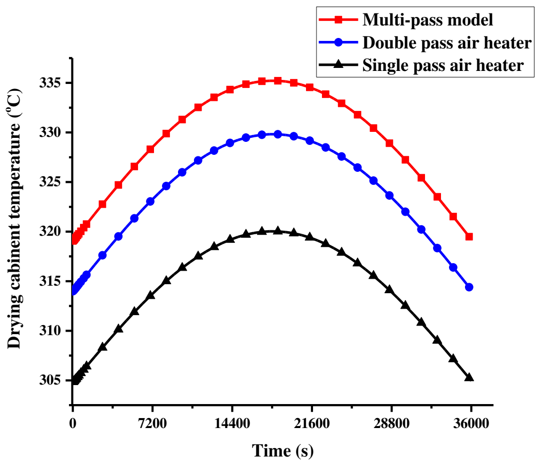

Figure-4. Temperature of drying cabinet at midday.

The system effective energy flux flow from the solar collector to the drying compartment was remained constant after a closed loop control mechanism of multi-pass was imposed. Figure-5 shows the closed loop profile in which energy flux of 471.2 Js^{-1} was maintained for a long period. This falls within the range established to dry selected farm crops like chilli and red bell peppers whereas *melastoma malabathricum* and *ortho siphon stamineus* were considered under medicinal herbs drying category [10].

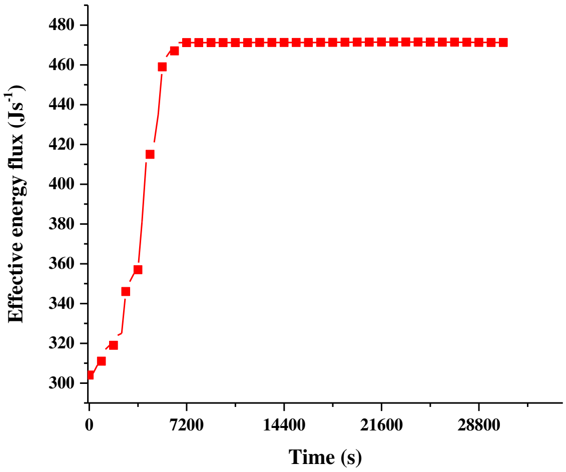

Figure-5. Energy flux under closed loop control.

The performance efficiency of the model was compared with the laboratory experimentation using humidity test chamber. The laboratory test was more efficient. This is due to the fixed humidity throughout the drying operation. However, the humidity is transient in reality which is reflected in the present model (Figure-6).

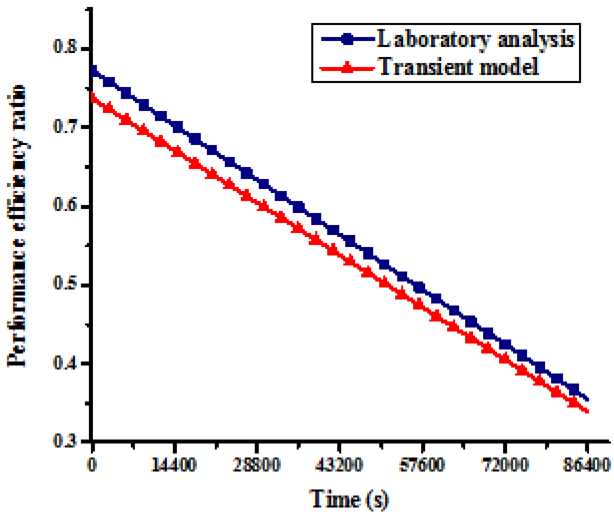

Figure-6. Laboratory analysis and model performance.

CONCLUSIONS

The lumped parameter simulation of multi-pass solar air heater under the dynamic situation has been presented. The closed loop approach was employed. A performance efficiency of 73.72% was predicted for drying system. The results of model were compared with reported publications with high correlative factors, which depicted the relevance of the system for effective and efficient drying of chili and some medicinal herbs [10, 16, 17]. The outcome of this study has laid a foundation for further investigation on SIMULINK/SIMSCAPE

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modeling and experimentation of solar thermal systems. However, improvement was still required on the model to improve accuracy and accommodate a choice of using composite materials for the system boundary.

Nomenclature

T	Temperature (K)
t	Time (s)
k	Material thermal conductivity ($W(mK)^{-1}$)
$\dot{Q}$	Rate of heat transfer (Js^{-1})
A	Area (m^2)
h	Thermal transfer coefficient ($Wm^{-2}K^{-1}$)
M	Moisture content (kg)
C	Crop constant
I	Irradiance (Wm^{-2})
l	Characteristic length (m)
B_i	Biot Number

Greek symbols

ρ	Density (kgm^{-3})
λ	Thermal diffusivity (m^2s^{-1})
α	Absorbance
τ	Transmittance
ϕ	Thermal constant
Φ	Radiative heat transfer coefficient between the plate and drying chamber

Subscripts

p	Plate
s	Solar
amb	Ambient
g	Glass
f	Fluid

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